IGNEOUS VS IMPACT PROCESSES FOR THE ORIGIN OF THE MARE LAVAS

VIVIEN GORNITZ
Goddard Institute for Space Studies, New York, N.Y., U.S.A.

(Received 6 December, 1972)

Abstract. In spite of chemical and petrological data furnished by the early Apollo missions, disagreement has persisted as to the ultimate origin of the mare lavas – were they true igneous magmas or impact melts? Examination of Lunar Orbiter and Apollo photographs of Tsiolkovsky, Mare Orientale and Humboldt crater, as examples of mare-filled impact structures, has suggested the answer.

It has been found that the mare lavas possibly stem from internal melting because a considerable time interval has elapsed between the time of basin excavation and basaltic extrusions. This was most effectively shown by crater counts on the ejecta blanket and mare filling of Mare Orientale. The central mare filling is distinctly younger than the ejecta cover, as shown by the lower crater densities on the mare surface as compared with the ejecta. Furthermore, many craters on the ejecta blanket of Orientale were flooded by lava long after the impact had occurred.

Mare-type lavas are not only confined to large circular impact basins, but also fill irregular depressions, like Mare Australe, where evidence for different flooding episodes has been observed.

1. Introduction

The 'hot' vs 'cold' Moon controversy persisted until quite recently, in spite of the availability of Apollo 11 and 12 lunar samples. Although the rocks returned by the astronauts clearly have crystallized from a melt, the important distinction between internally-generated magmas as opposed to molten rock produced by meteorite impacts had not been completely resolved.

Mare basins lie at the end of a continuous progression extending from micro-pits on lunar glass beads and rocks, to small surface impact craters, to larger ones like Tycho, then to partially mare-filled craters, like Tsiolkovsky and finally to the completely flooded basins like Mare Imbrium. A photogeological study of Lunar Orbiter and Apollo photographs has investigated the modification of impact structures by apparent igneous processes, in order to determine whether mare lava melted as a consequence of impact explosions, true volcanic activity, or a combination of both ('impact-induced volcanism'). Representative examples in this sequence have been examined in detail. These include Tycho, Aristarchus, Humboldt, Tsiolkovsky, Mare Orientale and Mare Australe.

The circular maria have developed in at least two distinct stages: (1) excavation of the basins; (2) subsequent filling of these depressions by dark, smooth lava (Baldwin, 1963).

The time gap exemplified by those craters that formed after the mare basin, but before its flooding (e.g., Archimedes in Mare Imbrium), is a general feature of all mare-highland contacts. Mare flooding was accompanied by subsidence of craters toward the mare (e.g., Doppelmayer in Mare Humorum). This hiatus suggests that the mare lavas did not melt instantaneously but were emplaced by internal igneous

The Moon **6** (1973) 357–379. *All Rights Reserved*

activity or impact-induced volcanism. Mare basins were created over a period of time as determined by overlap of ejecta blankets and the degree of morphological preservation.

2. Tycho and Aristarchus – Fresh Impact Craters

Tycho (84 km diam) and Aristarchus (40 km) represent examples of young, unequivocal impact craters with well-preserved features. Features resembling terrestrial lava flows have been observed on their flanks (L.O. V 125–128 and V 194–201). The radial distribution of the flows around the craters has been mapped from lunar photographs. Flows emanate at the rim crests, whether or not they continue into or outside the crater. These features were originally molten, as shown by the ropy texture, contraction fractures (shrinkage cracks) and flow lobes. They could have originated by impact melting, or internal igneous activity, perhaps triggered by impact. Smooth material fills hollows on the rims of these craters ('lava pools').

Strom and Fielder (1970) find, from crater counts, that the succession of flows on the outer rims of Tycho and Aristarchus extended over a considerable time interval, and that they are therefore volcanic in origin.

3. Humboldt Crater

Humboldt crater (200 km diam) on the Moon's southeast limb forms another link in the sequence from undisputed impact craters to the lava-filled circular maria. Humboldt exhibits most of the characteristics of fresh impact craters (ejecta cover, scalloped slump terraces and central peaks). Although it is relatively young (probably of Eratosthenean age – it is rayless, but secondary craters are still visible), its floor has undergone extensive post-impact modification, but extrusion of mare-type lava has only reached an incipient stage (Figure 1a).

The rough, hilly unit on the northern half of the floor may represent the remnant of the original surface (compare with the floors of Aristarchus or Tycho). To the south and east, it is blanketed by a smooth, light plains-forming unit, like the Cayley Formation (Figure 1b). The plains-forming unit was probably not a fragmental, erosional layer (regolith) which otherwise would have covered the entire floor uniformly. Its confinement to the southern half of the crater, which coincides with the distribution of rilles, may suggest internal causes such as perhaps an ash flow unit. The floor, including the central peaks, and particularly on the plains formation, is dissected by a complex rille system resembling a spider-web. The rilles in turn have been truncated in several locations by patches of mare material, presumably basaltic lava, which may have issued from the fractures they conceal (Figure 1c). The rille system consists basically of radiating and concentric fractures that could have formed in response to slow isostatic uplift of the floor. The crust may have been thinner or less viscous than elsewhere. Stresses were confined to the crater and were not part of a larger system. Apparently, forces of internal origin have contributed to the post-impact development of Humboldt.

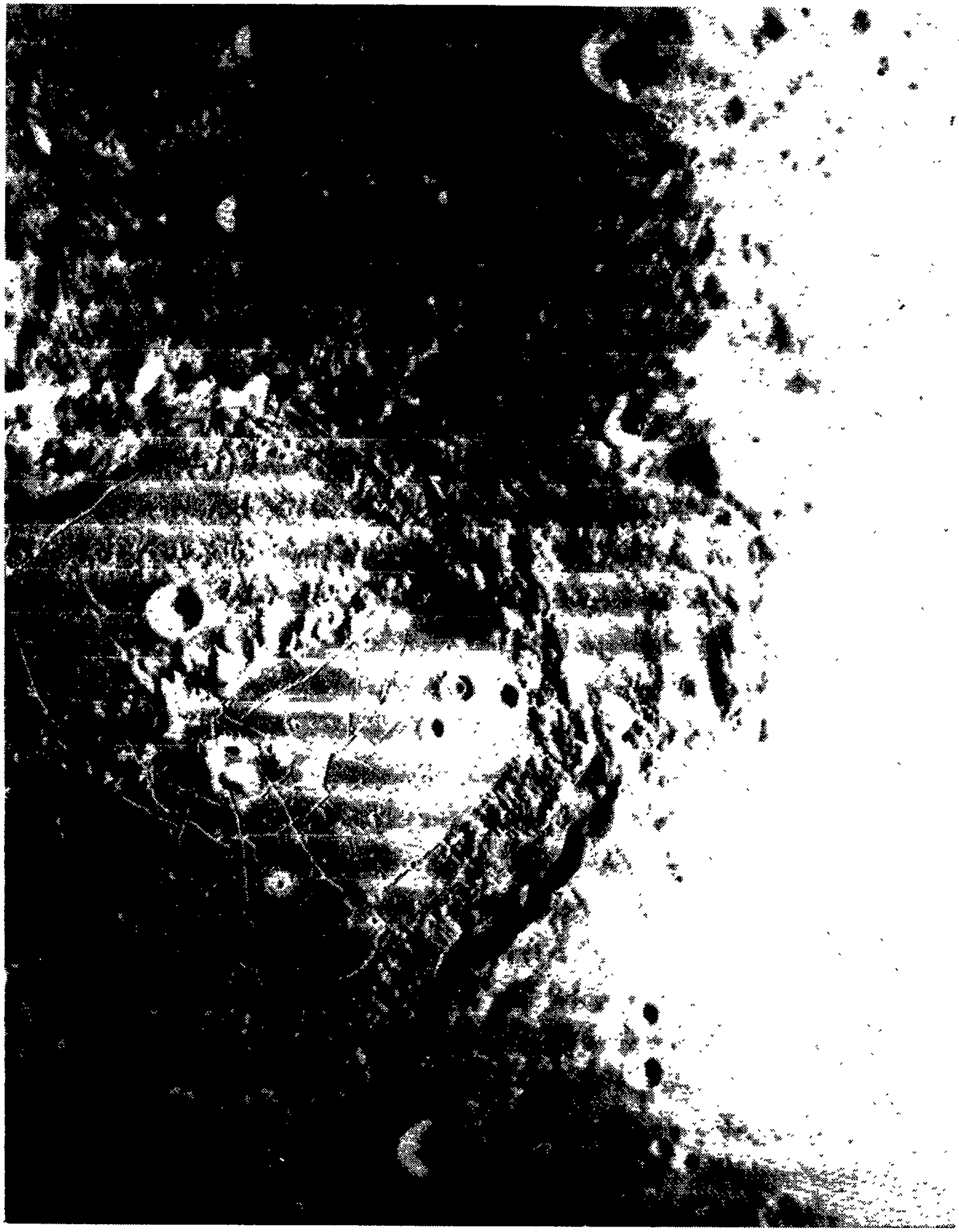

Fig. 1a. Humboldt Crater – vertical view (Lunar Orbiter IV-27H).

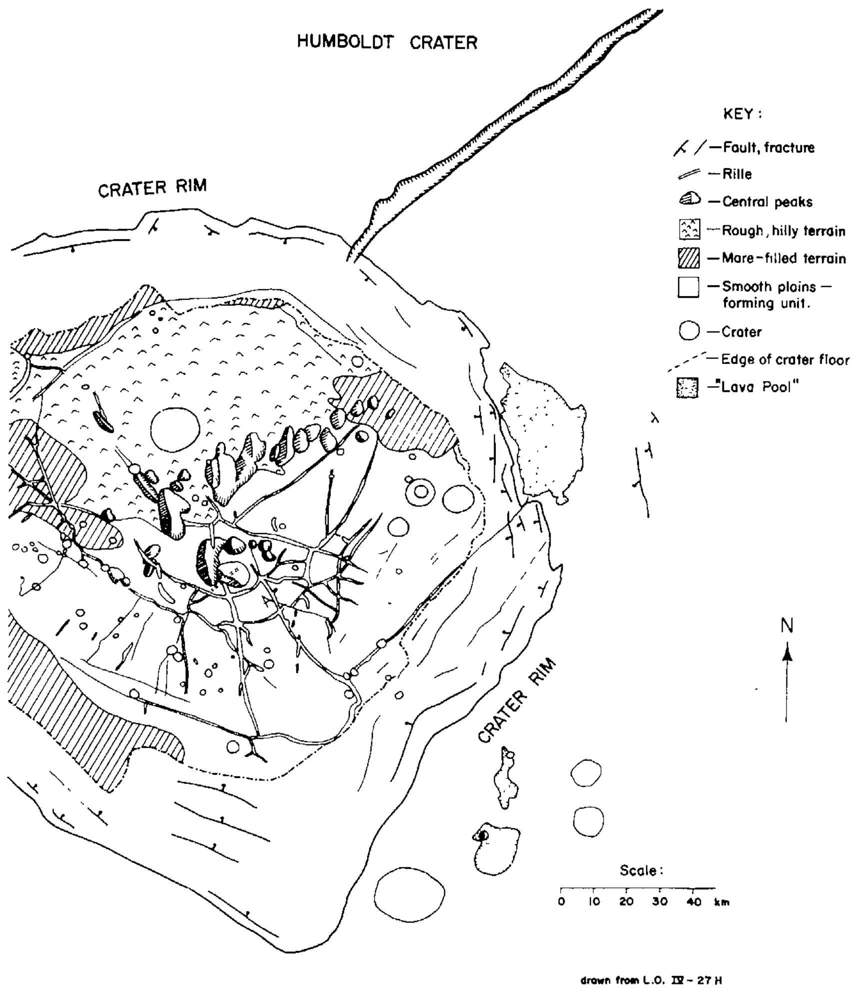

Fig. 1b. Geologic sketch map (drawn from L.O. IV-27H).

4. Tsiolkovsky Crater and Surroundings

4.1. Summary of History Deduced from L.O. Photographs and Prepared Geological Maps

Tsiolkovsky crater (200 km diam) is a relatively young impact crater on the lunar farside (20° S, 129° E), which is distinctive because of its dark, smooth mare-flooded floor (Figure 2). Evidence for an impact origin is found in the raised hummocky rims, ejecta blanket and base surge deposit (well-developed on the western side), and secondary crater chains and clusters radial to the crater (Guest and Murray, 1969). Like many other large craters of this type, Tsiolkovsky exhibits slump terraces on its inner walls and central peaks which now form a heart-shaped island in the mare. Slump fractures are preferentially aligned in NE-SW and NW-SE directions, apparently controlled by the 'lunar grid'. Other fractures trend N-S; as observed by the Apollo 15 astonauts. Parts of the original premare floor remain, especially in the NW and SW quadrants, where one can still see the initially irregular surface – rounded hills and faint fractures

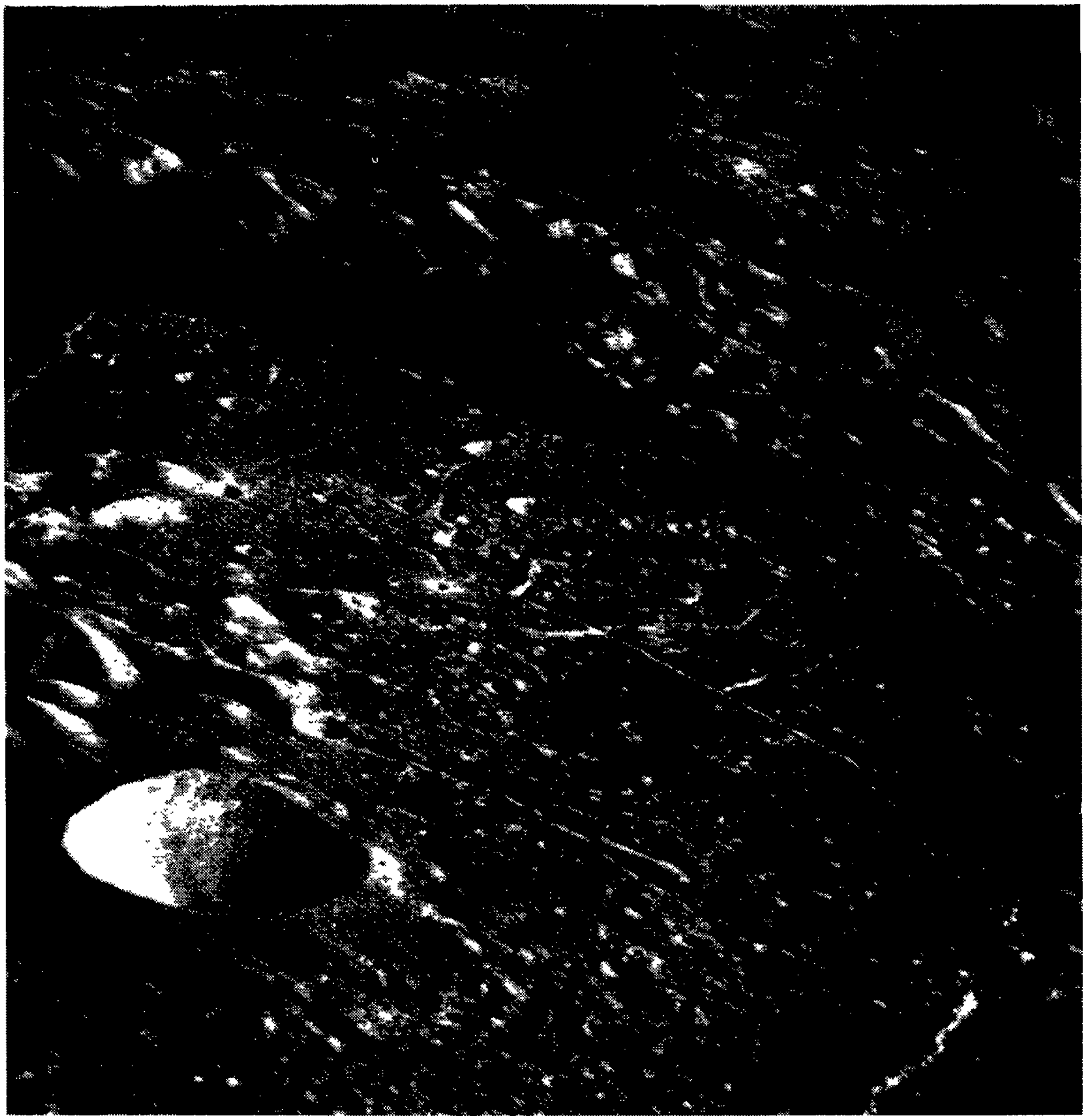

Fig. 1c. Humboldt – oblique view – Apollo 15 photograph (15-12645).

parallel to the edge of the inner wall (Figure 3a). This surface resembles the floors of Tycho or Copernicus, and may represent impact-melted material. As was the case for Tycho and Aristarchus, land-slides occur along the inner walls. However, at he resolution of the L.O. photographs, one cannot distinguish between once molten flows as opposed to debris slides. There are also depressions on the outer rim filled with smooth, plains-forming material (e.g., Cayley-like unit), similar to the 'lava pools' of Tycho, but these are of intermediate albedo (Figures 2 and 3a).

The sequence of events at Tsiolkovsky is relatively simple. The impact explosion was followed closely by base-surge* and ejecta blanket deposition, which is marked

* A horizontally moving gas-solid suspension, formed either by volcanic eruption or by a violent explosion. In this case, it evidently was produced by the impact.

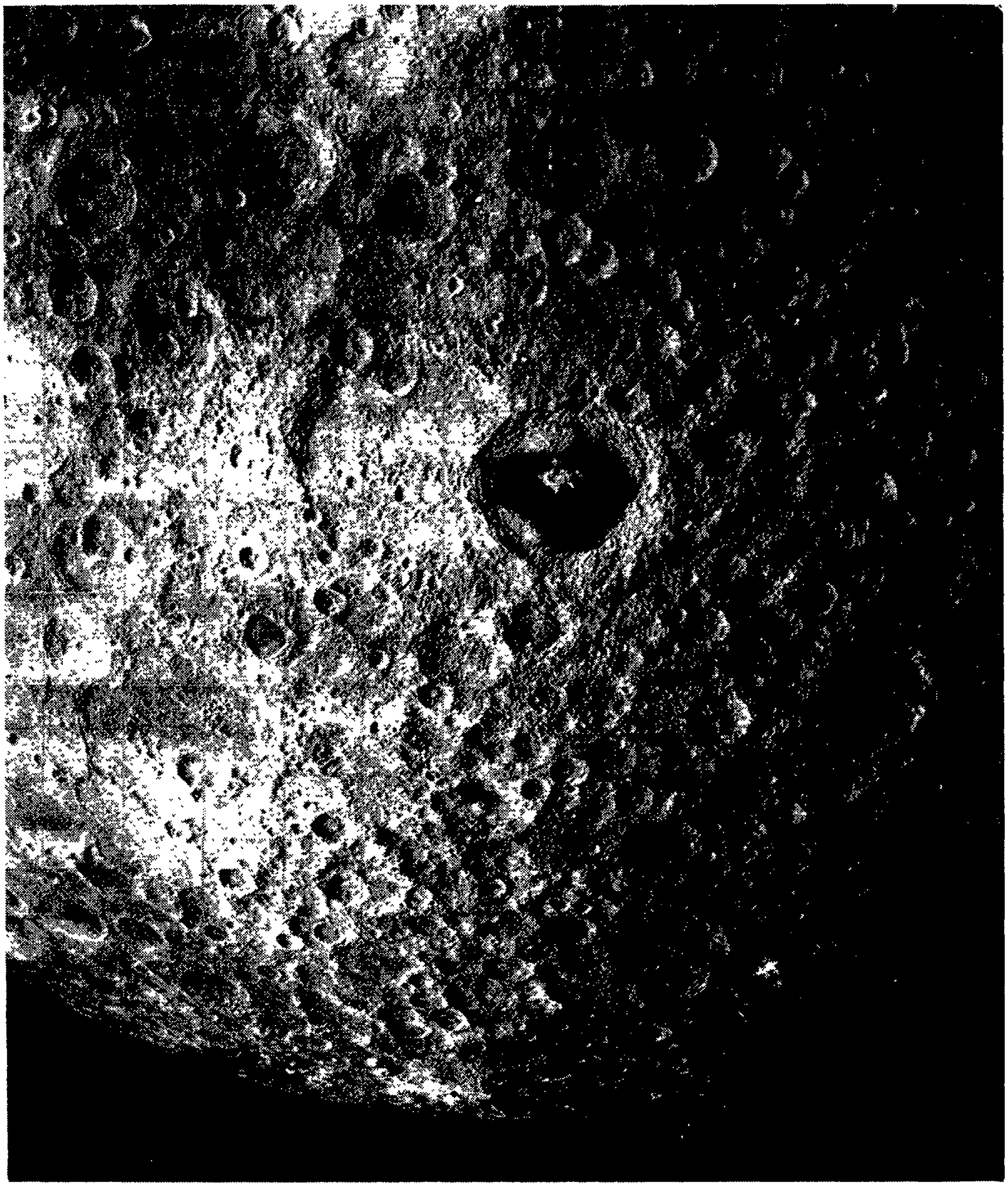

Fig. 2. Tsiolkovsky Crater (Lunar Orbiter III-121M).

by radial grooves or lineations on the western side of the crater (its development on the eastern side, in shadow, may not have been as pronounced). The base surge deposit forms a prominent unit in the NW quadrant of Tsiolkovsky, resembling a flow.

This stage was closely followed by slumping of the inner walls, landslides, and the formation of the crater floor and central peaks. Lastly, the floor was flooded by mare-like material, now believed to be basaltic lava, emerging from fractures or

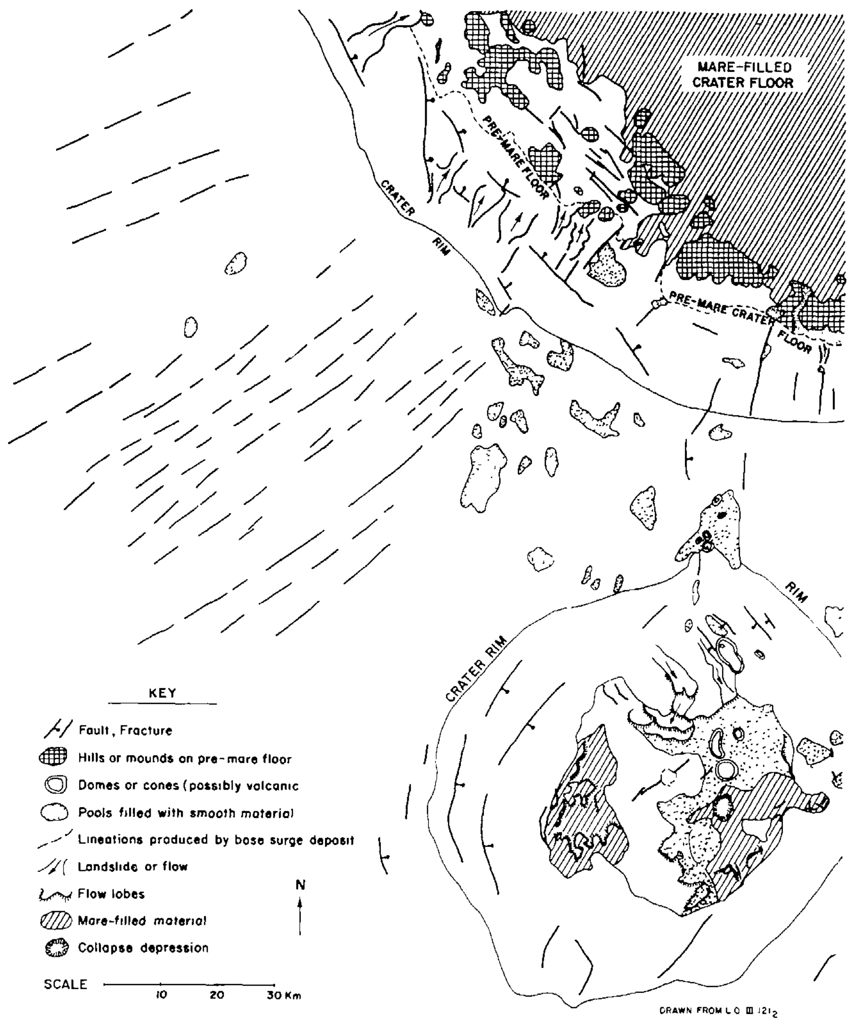

Fig. 3a. Geologic sketch map of the SW quadrant of Tsiolkovsky Crater and Waterman crater (drawn from L.O. III-121H).

fissures beneath the crater. The eruption of lava probably occurred shortly after the impact, as determined by relative crater densities (see below). At least one landside formed after the mare filled (it encroaches on the mare).

4.2. Evidence for volcanism in the vicinity of Tsiolkovsky

Due south of Tsiolkovsky, Waterman crater (80 km diam) displays many curious features. Waterman is an old crater, formed prior to the impact of Tsiolkovsky, yet its floor is covered with a complex pattern of flows, depressions, dark patches of mare-material and raised hills (perhaps volcanic domes) younger than Tsiolkovsky. One of the flows (northern part of floor) has cascaded down the side of the crater from a smooth-floored pool covered with small volcanic hills, one of which has a summit pit (Figure 3a).

Other partly mare-filled craters in the area include Bolyai, south of Waterman (35° S, 125° E), and Langemak, NW of Tsiolkovsky (10° S, 119° E) (Figure 3b). Flow-

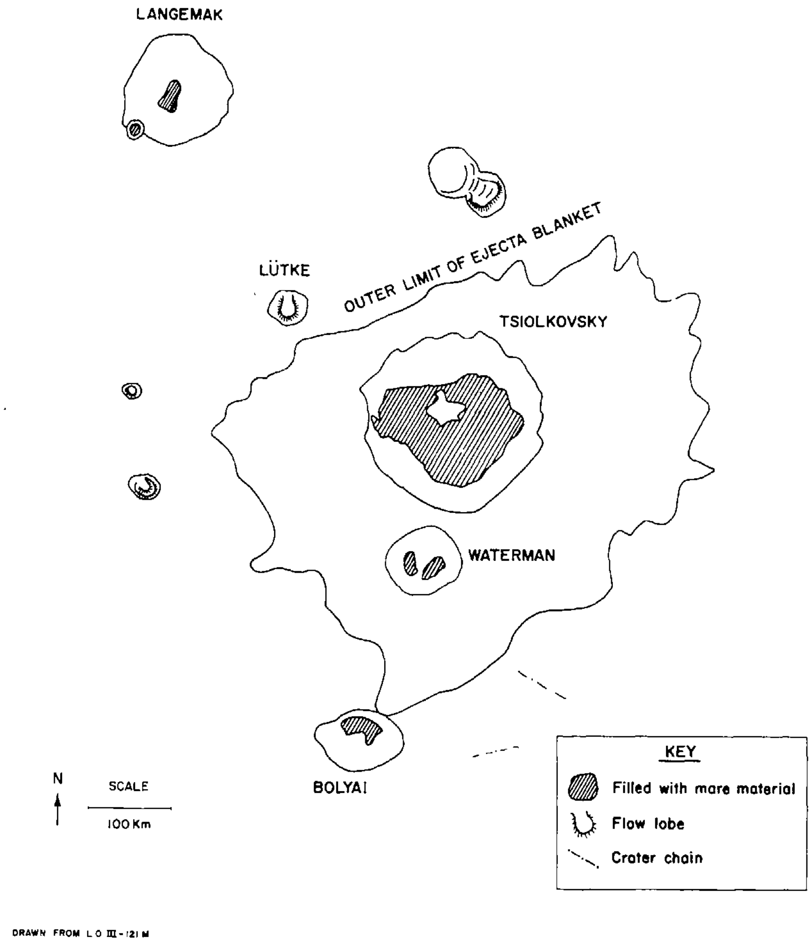

Fig. 3b. Index map showing locations of mare-filled craters in vicinity of Tsiolkovsky.

like features are apparent at Lütke (17° S, 121° E), Izsak (23° S, 117° E) and in a pair of overlapping craters at 12° S, 129° E. Material from one crater appears to have overflowed into the other. The distinction between lava flows or landslides is not clear-cut (Figure 4).

4.3. Relative Ages of Various Surface Units by Crater Counts

A closer study of Tsiolkovsky can reveal details of the mare-forming process since this crater displays the effects of both meteorite impact and volcanism. The time at which the lava was extruded relative to the time of impact could limit choices as to the source of the lava. Naturally, if the dark smooth filling consists of lava melted by the energy of impact, it could not be much younger than the ejecta blanket. If, on the other hand, internal volcanism generated the lava, its age could range anywhere from the time of impact to the present. An igneous origin can be established unambiguously only if the lava is much younger than the ejecta blanket. For this reason, crater densities were measured on both ejecta cover and mare filling of Tsiolkovsky, and compared with densities for two typical mare sites.

Fig. 4. Double crater with flow or debris slide emanating from one crater into the other (Apollo 15-12745, 6).

If we assume that most lunar craters are formed by a random impacting process of uniform rate, then the more heavily cratered a given area the older it is. (Due to uncertainties in the change of flux rate with time, absolute ages cannot be reliably determined by this method.)

Crater densities were determined for two mare sites at Mare Tranquillitatis and Oceanus Procellarum (Figure 5). The curve for Mare Tranquillitatis plots above that of Oceanus Procellarum, suggesting that the latter is younger, as has been verified by absolute dating of returned lunar samples.

Crater densities for the ejecta blanket and mare-filling of Tsiolkovsky (L.O. III-121 H_2–H_3) are also plotted on Figure 5. Parts of the inner rim were included with the

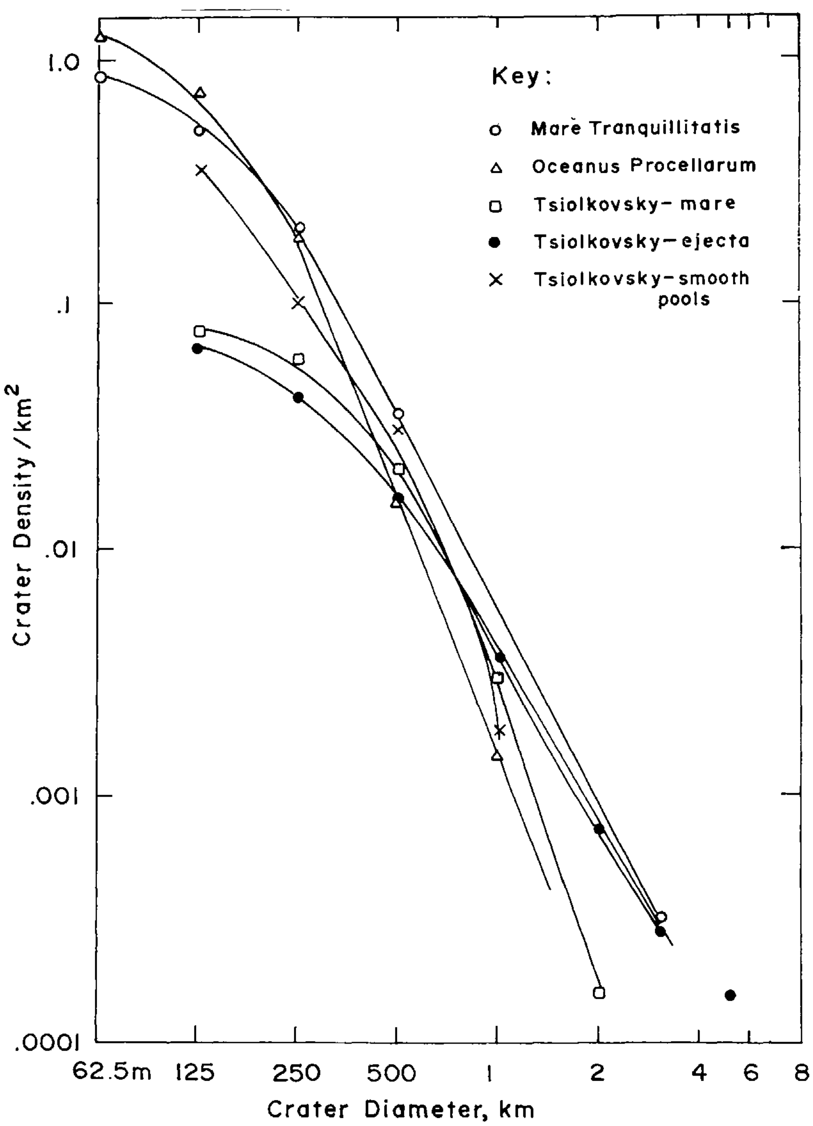

Fig. 5. Plot of crater density vs diameter for Tsiolkovsky and two mare sites.

ejecta blanket, under the assumption that they formed or shortly after the impact event.

The points for Tsiolkovsky lie on curves roughly between both mare sites, suggesting an age intermediate between the two. For craters greater than 500 m, the crater density of the ejecta blanket lies above that of the mare-filling, showing that it is indeed older. However, for smaller craters, the reverse is true. This puzzling result could indicate the presence of numerous small endogenetic craters on the mare-filled floor. Many are shallow, rimless depressions similar to collapse craters. Guest and Murray (1969) find crater clusters arranged in EW belts on the mare-filled floor, which they attribute to secondaries from an unspecified primary impact crater. Yet there are no large, fresh impact craters nearby which could have supplied the secondaries. Alternatively, erosion may have been more rapid on the steeper crater walls and slopes of hummocky ridges. These areas are deficient in craters, which were probably destroyed by downhill creep. Inclusion of these areas into the total may have lowered the ejecta crater density relative to the mare-filling.

The smooth pools on the ejecta blanket are expected to be younger than the surrounding ejecta formation, yet their crater density exceeds that of either the ejecta cover or basin filling. This peculiar relationship may be explained either by endogenetic crater production in the pools or more rapid erosion on the surrounding slopes. A similar situation was found by Mutch and Saunders (Hommel Quadrangle Map, 1968) and also by Greeley and Gault (1971) who interpreted the excess crater density in the interior terraces of Copernicus to be caused by endogenetic collapse craters in basalt.

The Apollo 15 astronauts observed that the 'base-surge' or 'rockslide' unit was bounded by a double fault system. They also pointed out that the base surge deposit appeared to have a higher crater count than Fermi, the ancient, degraded 230 km crater west of Tsiolkovsky, whose floor is covered by the deposit. The excess of craters has been attributed to outgassing, and/or collapse of material back into the blocky subsurface. On the other hand, this increase, visible only in the smallest size ranges (<0.5 km) may reflect the 'non-equilibrium' nature of the relatively young surface. The number of craters on a surface increases rapidly at first, but due to repeated bombardment, eventually attains an equilibrium value in which the rate of crater production equals the rate of destruction. The older floor of Fermi may have attained an equilibrium value – whereas the ejecta blanket or base surge has not, making the latter look more heavily cratered for its age. Guest and Murray (1969), for instance, find the maximum crater density on the ejecta blanket clustered in a ring around Tsiolkovsky 120 km from the rim, way in excess of values farther out on the pre-Tsiolkovsky surface. This excess has been produced by the rain of secondary craters, accompanying the impact.

The results suggest that Tsiolkovsky formed some time between M. Tranquillitatis and O. Procellarum (that is, 3.2–3.6 b.y. ago). The mare filling is not significantly younger than the ejecta blanket. Based upon crater measurements alone, the lava may derive from either internal or external forces. However, other evidence points to an igneous origin. For instance, the remnants of the pre-mare floor resemble the floor of Tycho or Aristarchus. This rough surface may have formed by shock melting, following impact. The dark mare material is stratigraphically younger than the rough surface, since it embays it. The dark color suggests a difference in composition as compared with the rest of the crater, which in turn implies igneous differentiation. (The Apollo 15 astronauts noted that the mare surface was not as dark visually as on photographs. Thus the surface may be older than anticipated from its low albedo, or may not differ as much chemically from the surrounding highlands.) The excess of smaller craters on the mare-flooded floor and the smooth pools of Tsiolkovsky may be caused by endogenetic (volcanic) processes.

5. Mare Orientale

Because Orientale is the youngest of the large multi-ring basins, its history may therefore serve as a model for the origin of the maria.* Mare Orientale has been shaped by both meteorite impact and volcanism. The role of each of these processes will be evaluated.

5.1. Geologic Setting

The Orientale basin is situated on the SW limb of the Moon as seen from Earth. Prior to the Lunar Orbiter missions, it was visible by telescope only under rare conditions of favorable libration.

Orientale basin is surrounded by five concentric rings (Table I). The most prominent ring, formed by the Cordillera Mountains, is about 900 km in diameter and rises

TABLE I

The concentric rings of Mare Orientale

Ring No. (innermost first)	Diameter, km (this study)	Diameter, km (Van Dorn, 1969)	Ratio relative to first ring	Ratio with preceding ring
1	375 km	360	1.0	–
2	478	480	1.27	1.27
3 Rook Mts.	612	620	1.63	1.28
4 Cordillera Mts.	905	930	2.4	1.48
5 ‘Rocca’ ring	1295	1360	3.44	1.43

some 3000 m above the surrounding plains (Figure 6). The mare occupies most of the innermost ring, 375 km in diameter. Smaller arcuate patches of mare material occur at the base of the Rook Mountains (Mare Veris) and the Cordilleras (Mare Autumni). The area between the central mare and the Rook Mts. consists of highly fractured, rough, hilly terrain, much like the floors of Tycho or Aristarchus, which may represent impact-melted material. The zone between the Rook and Cordillera Mts. (Montes Rook Fm; McCauley, 1968) is somewhat less rugged, but contains numerous closely spaced hummocks and faint radial lineations. Only beyond the Cordillera, a blanketing unit appears, which has a radially grooved, braided herring-bone texture (Cordillera Fm.). This rock formation completely surrounds Orientale, but is more extensively developed in north, south and west directions. The texture becomes progressively less pronounced with increasing distance from the center. This ejecta blanket (by analogy to smaller impact craters) provides strong evidence that the Orientale basin has been blasted by an explosive asteroidal impact. The outermost ring is located on the ejecta cover and consists of a low irregular ridge that includes the walls of some pre-impact craters.

* Hartmann and Kuiper (1962) have shown that most of the circular maria are surrounded by concentric structures similar to Orientale, which have been more severely degraded by subsequent meteorite bombardment.

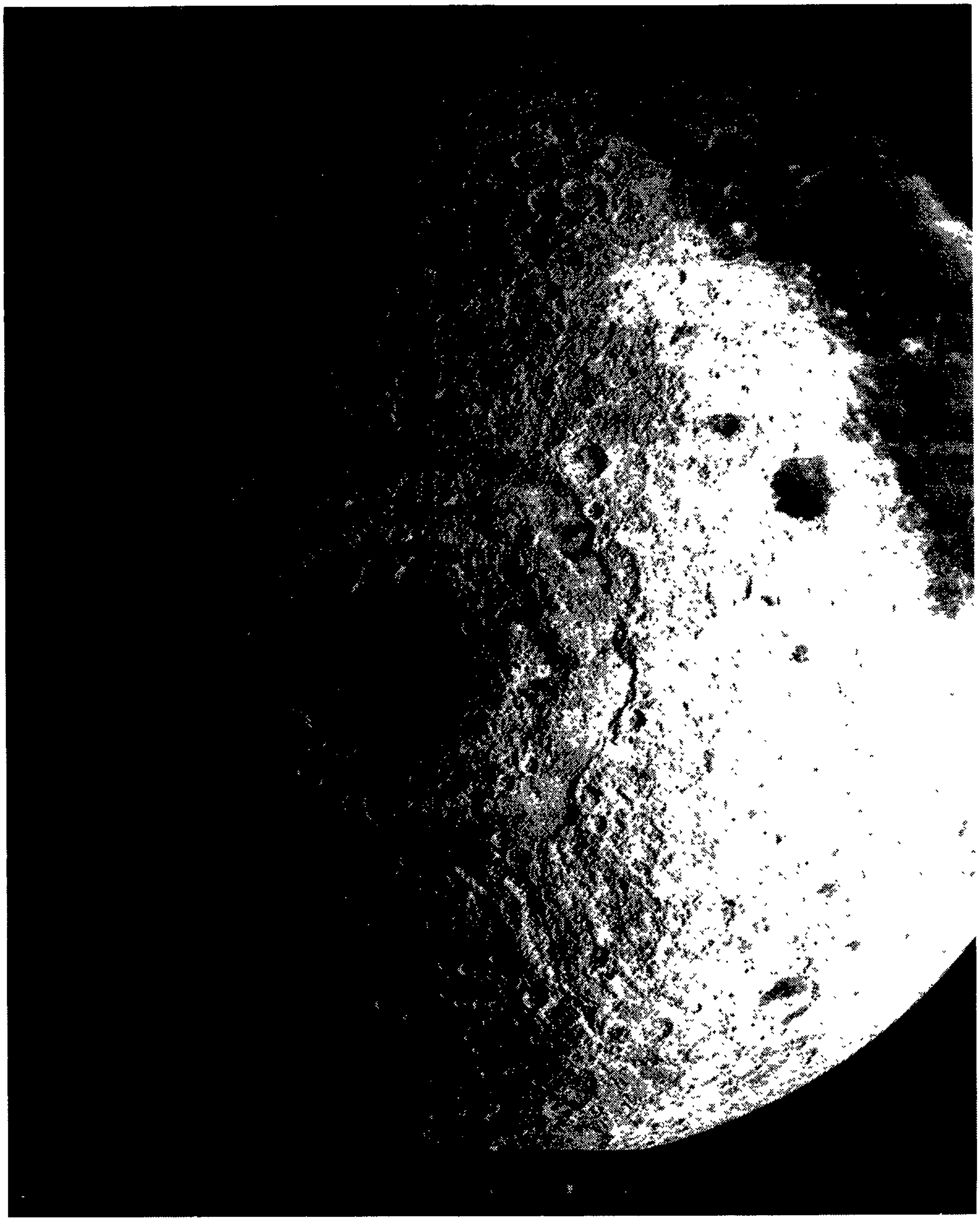

Fig. 6. Mare Orientale (Lunar Orbiter IV-187M).

The Orientale ejecta blanket has thinned to such an extent before reaching the western edge of Oceanus Procellarum that it is difficult to establish whether the ejecta cover is overlapped by the mare. However, McCauley (1967) has interpreted the Hevelius Fm. (the thinnest, smoothest facies of the ejecta) to be older than the Procellarian mare filling. The northeast trend of grooves and ridges, radial to Orientale in the Hevelius region, indicates that the moon has been structurally affected by the Imbrium event to distances greater than 1000 km from the center. Northwest and southwest of Orientale, secondary crater chains and clusters may be detected as far west as 140° W and up to 40° N, or distances of 1600 km from the center (see for instance, L.O. V-frames 21, 24, and 28).

5.2. Crater density studies

The time of emplacement of mare lavas relative to the impacting event places constraints on possible sources of the lava. A large time interval (as shown by a significant difference in crater density of the lava vs ejecta cover) would favor an internal origin; a short time interval would be indeterminate (see also Section 4 on Tsiolkovsky).

Crater densities were determined for (1) the southern part of the central mare filling (the northern half is discarded because it is covered by secondary craters from a nearby fresh impact crater), (2) portions of the Rook Fm., (3) Mare Veris, and

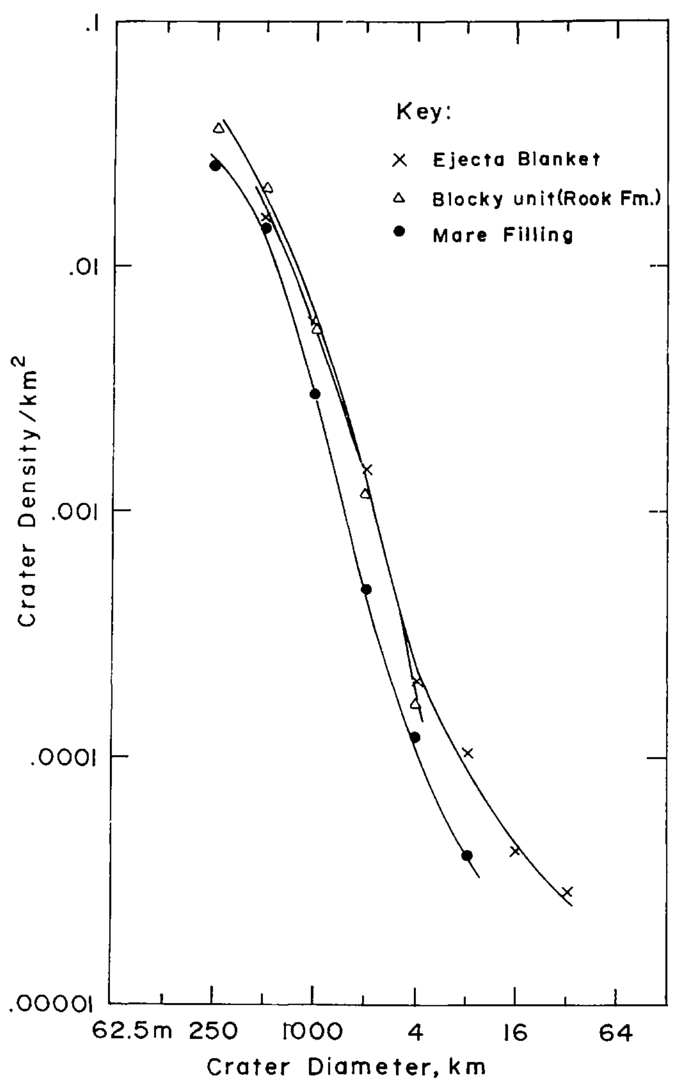

Fig. 7. Plot of crater density vs diameter for Mare Orientale.

(4) ejecta cover (Figure 7). Results are presented on the graph (Figure 7). The mare filling is distinctly younger than both the ejecta cover and the Rook Fm., because its crater densities are lowest. (Mare Veris is roughly the same age as both the ejecta cover and Rook Fm.) Orientale basin formed at the time or slightly before Mare Tranquillitatis (~3.7–4.0 b.y. ago), early in the mare-filling period. This is in substantial agreement with Hartmann and Yale (1968).

5.3. Structural Development of M. Orientale

The structural development of the Orientale basin was a complex, multistage process (Figure 8). The fault scarps defined by the Cordillera Mts. show possible post-ejecta movement (see L.O. IV-181H). The portion of the cliff near Eichstadt Crater (52 km diam) and to the south appears blanketed by the ejecta (slope 12°, 1.7 km high), while north of this crater and near Kresnov crater, the scarp is steeper (18° slope) and higher (2.5 km). Either the subsidence was uneven to begin with or there was renewed faulting after the impact.

Parts of a concentric and radial rille system are truncated by the eastern part of Mare Veris (Figure 9a). If Mare Veris is approximately the same age as the ejecta blanket, as implied by the crater density, then this rille system must have formed at the time of the impact, in response to the stresses produced by the cataclasm. On the other hand, the complex assemblage of rilles parallel to the southern edge of Mare

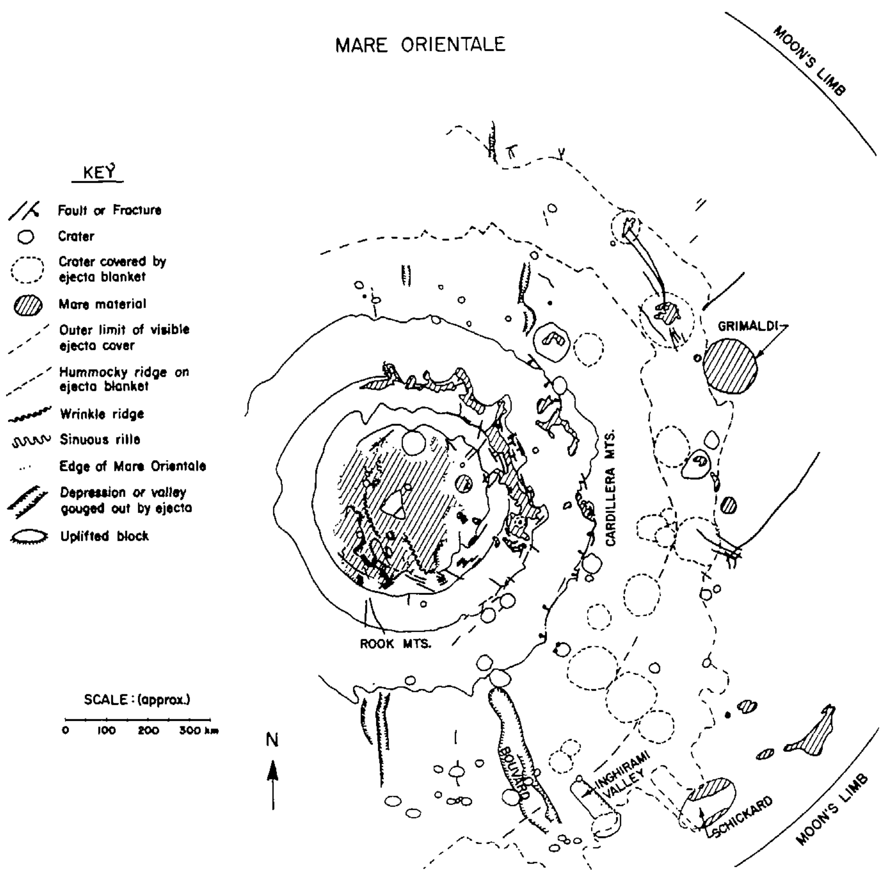

Fig. 8. Geologic sketch map of Mare Orientale (drawn from L.O. IV-187M).

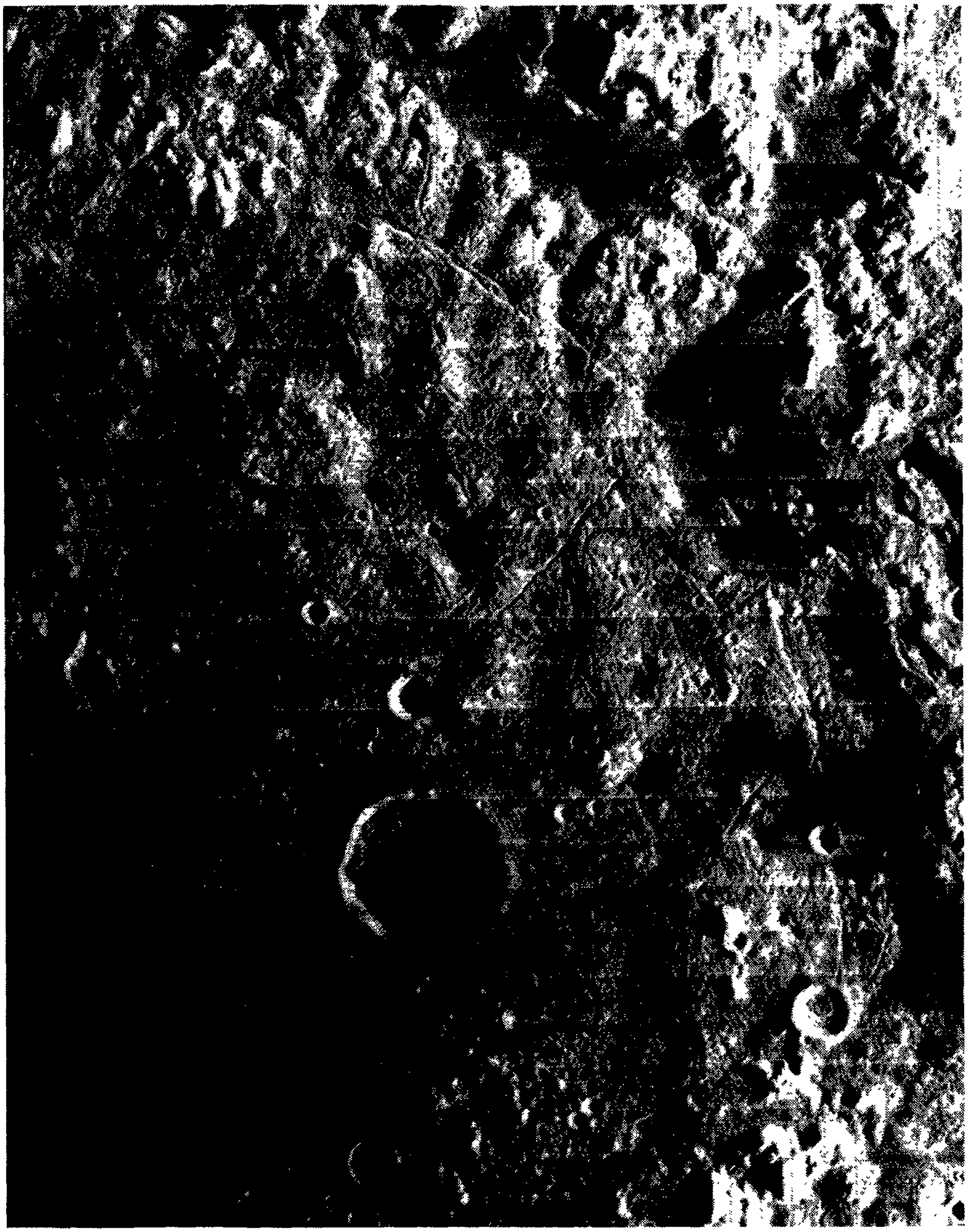

Fig. 9a. Concentric and radial rille system in Mare Veris (L.O. IV-187H_2).

Orientale has evidently formed soon after the mare was emplaced – in other words, substantially later than the impact (Figure 9b). The association of these rilles with collapse structures, domes, and wrinkle ridges suggests an internal origin for these features, linked to the extrusion of lava.

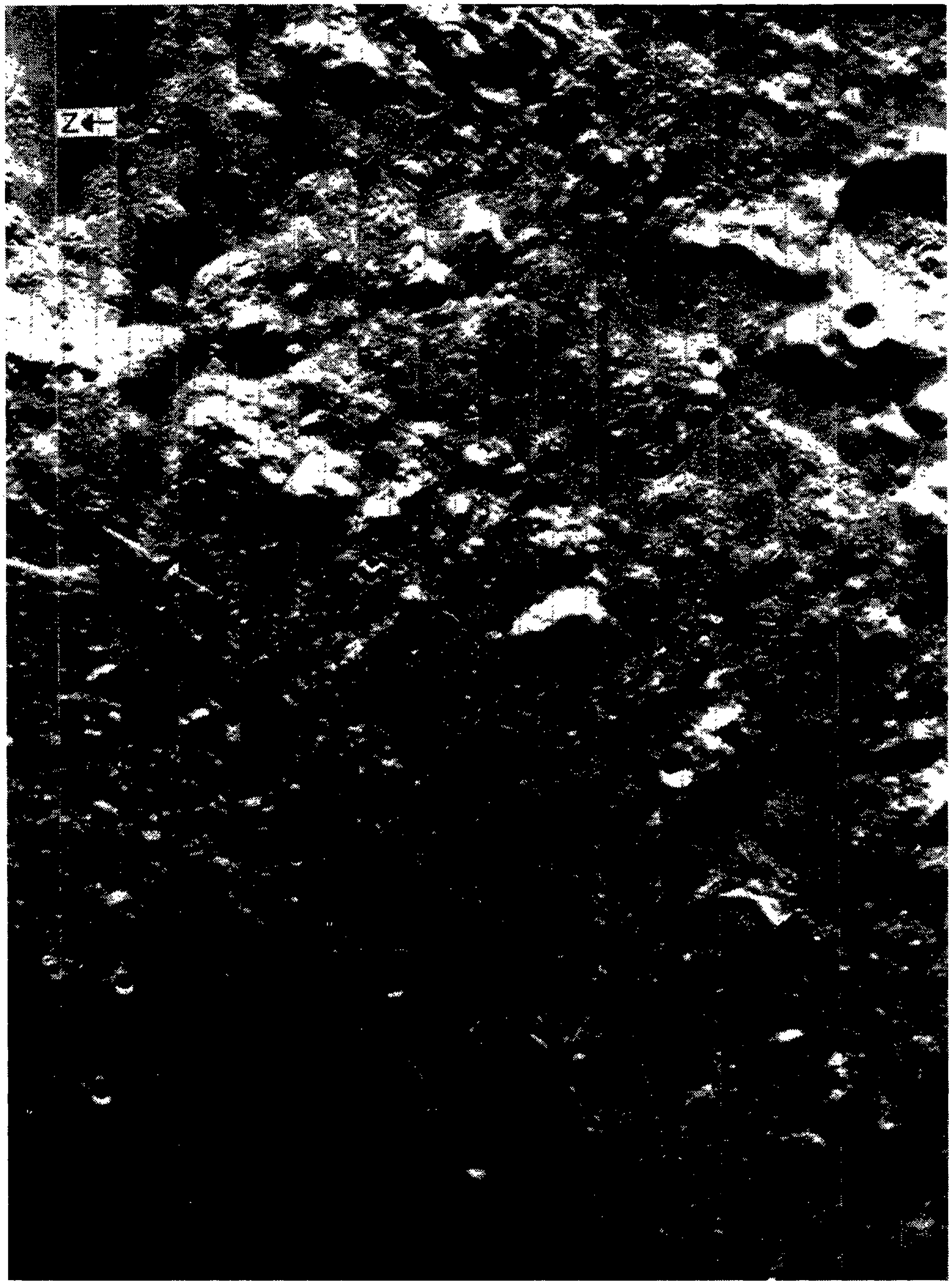

Fig. 9b. Complex rille pattern on southern edge of Mare Orientale (L.O. IV-187H_1).

5.4. Volcanism in Mare Orientale Basin

The southwest corner of the mare may represent a volcanotectonic sink structure, created by magmatic activity. The numerous, circular, rectangular and irregular depressions probably have resulted from collapse, following the diminution in volume of the magma chamber on cooling and losing its volatiles. Such settling and buckling of the subsurface could have also produced the swarms of rilles in the last stages of mare filling. Some rilles change into straight ridges showing that lava had formed its way up these fissures (dikes). Two sinuous rilles grade into straight rilles suggesting that they may be tectonic in nature. Associated with the collapsed areas are upraised blocks, upon which domes have grown.

Wrinkle ridges are concentric with the mare boundaries (as in other circular maria) and also appear along the 'shores' of premare 'islands'. They may represent the sources of the latest lava flows. Kopff crater ($\sim$40 km diam) on the eastern edge of the central mare may be a volcanic calcera (Figure 9a). It is a relatively young crater, but has a smooth rim flank without a hummocky to radial ejecta blanket or secondary crater chains. The steep inner walls, lava covered floor with irregular rilles and flows that spilled over north and south rims support this conclusion. A deep gouge on its outer flank may also be of internal origin. One dark-haloed crater is present on the mare floor. Such craters, common near Copernicus and on the floor of Alphonsus, are generally considered to be maars (explosive volcanic vents) surrounded by ash deposits (McCauley, 1969, Alphonsus GA map).

Endogenetic features of Mare Veris include crater-chain rilles, dark-haloed craters, upraised areas topped by summit-pitted domes or rilles, and a few sinuous rilles. A ghost crater indicates that a short time interval elapsed between the impact and flooding of Veris. An elliptical crater near the edge of M. Veris filled with bulbuous mounds could be a viscous extrusive (Figure 9a).

In Mare Autumni, a sinuous rille, a dike transecting a wrinkle ridge and flow fronts illustrate volcanic activity.

Several craters in the vicinity of Orientale were filled with mare material (probably basaltic lava) after the main impact explosion (see Figure 6). Schlüter crater (98 km diam) on the Cordillera scarp is an old impact crater, resembling Tycho or Copernicus, with its scalloped terraces, some filled with a smooth plains-forming unit, central peaks and a rough floor half-filled by younger mare material. It is quite old since its own ejecta blanket is barely visible, yet it formed after the Orientale event. Upwelling of lava could have occurred along any of the numerous rilles on its floor.

Riccioli (150 km diam) is 750 km northeast of the center of Mare Orientale. The crater is older than the Orientale basin, since it is blanketed by ejecta deposits. Yet, the center of this crater was covered with mare material later than the ejecta deposit.

Schickard crater has also been partially buried under Orientale ejecta. However, the north and south parts of the crater floor are covered by mare material that is evidently younger than the ejecta (because of a much lower crater density). Similarly, Grimaldi and Gruger craters have also been mare-filled after deposition of the Cordillera Fm.

The foregoing examples illustrate that the upwelling of lava in the center of Mare Orientale and several craters on its ejecta blanket occurred well after the asteroidal collision which generated the bulls-eye structure. Thus, the lavas were not strictly impact melts. However, a close relationship may have existed between the impact and subsequent volcanism. Although the magmas were probably internal (that is, generated by forces within the Moon), they travelled to the surface along impact-produced fractures. The lunar crust could have been fractured to depths of 180 km by the impact (Van Dorn, 1968).

The respective role of external vs internal processes may be summarized as follows. The inner Orientale basin (370 km diam) was formed by the explosive impact of an asteroidal body (est. diameter 80 km; Hartmann and Yale, 1963), with an energy of about 4×10^{31} erg (Baldwin, 1963). Within minutes after the impact, the concentric fracture system developed as an adjustment to the stresses generated by the shock wave (Figure 10a). The inner basin may have developed in as little as 3 min, if the formation time scales directly with the square root of the crater diameter (Gault, 1969). Movement of the crust along these fractures may have continued long after the impact. Fault blocks slid down toward the center of the basin. Van Dorn (1968, 1969) attributes

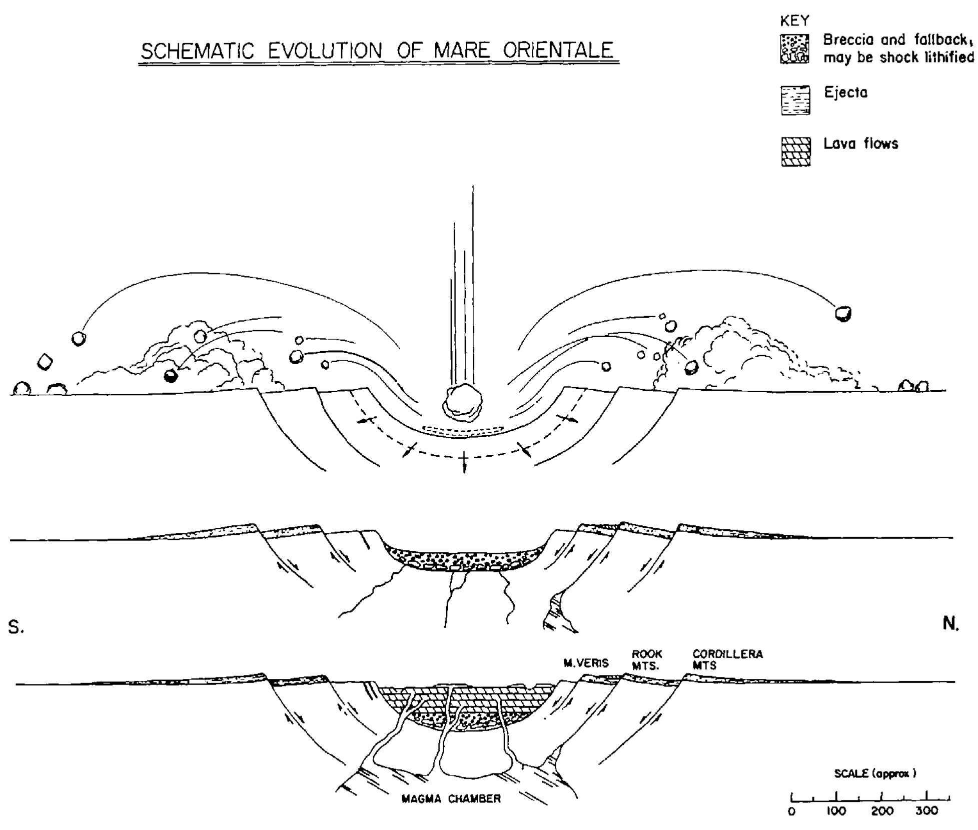

Fig. 10a-c. Stages in the structural development of the Orientale basin.

the regular spacing of the rings to the 'frozen' crests of a gravity wave following impact, which 'fluidized' the surface layer to a depth of 50 km. Mackin (1969) interprets them as slump scarps due to subsidence of the crust after vast magma and ash eruptions.

The rings could also represent fracturing in a solid crust as sites of maximum deformation. The ring structures of Mare Orientale are duplicated in miniature in micro-craters on lunar glass beads (Carter and MacGregor, 1970; McKay *et al.*, 1970). The structures formed after the beads had already solidified and thus indicate brittle fracture.

During the minutes following impact, the floor of the inner ring of Mare Orientale was shock melted, intensely brecciated and fractured. Simultaneously, a base surge cloud (horizontally moving gas-solid suspension) swept out beyond the Cordilleras to distances greater than 1000 km, concealing many craters in its path before being dissipated, while ballistically ejected blocks were raining down over the area. Assuming that the base surge cloud was traveling at speeds of 100 m s^{-1}, it would have taken 3 h to be deposited. (A base surge cloud closely resembles a nuée ardente or glowing cloud such as the one from Mt. Pelée volcano that in 1902 wiped out the town of St. Pierre in less than 6 min, and that was moving with a maximum velocity of 150 m s^{-1}; Rittman, 1962). The outermost ring (Rocca Ring) may be a buried fracture system or may consist of dunes deposited by the base surge as it was decelerated by topographic obstacles such as the walls of pre-existing craters. Valleys, such as Bouvard, belong to a family of radial rifts along which the flowing ejecta debris were channeled.

Lava emerged at the surface along fractures at the base of the Rook and Cordillera fault scarps (Figure 10b). The rocks may have been nearly molten prior to the impact or a fraction of the impact energy may have heated the rocks to their melting point. Nevertheless, volcanism continued for a considerable time after the shock wave had been dissipated (e.g., central mare flooding and mare-covered craters on the ejecta blanket; Figure 10c).

6. Mare Australe

Dark mare material is not always confined to large circular basins or craters which were initially excavated by meteorite or asteroidal impacts. In such cases, volcanism triggered by impact does not suffice to account for the effusion of lava. For example, Mare Australe, near the southeastern limb of the Moon, occupies an irregular depression which bears no sign of a former impact basin. The mare appears relatively shallow, because craters are filled to varying extents and the rims of many ghost craters project above the surface (Figure 11).

Different flooding episodes are marked by variations in albedo and crater density. The mare surface southeast of Humboldt is younger than in adjacent areas, because it is not covered by the swarm of secondary craterlets from Humboldt. Two crater superposed on the mare include Jenner (70 km diam, 96° E, 47° S) and Hamilton (65 km diam, 84° E, 48° S). The floor of Jenner, which resembles Tsiolkovsky, was

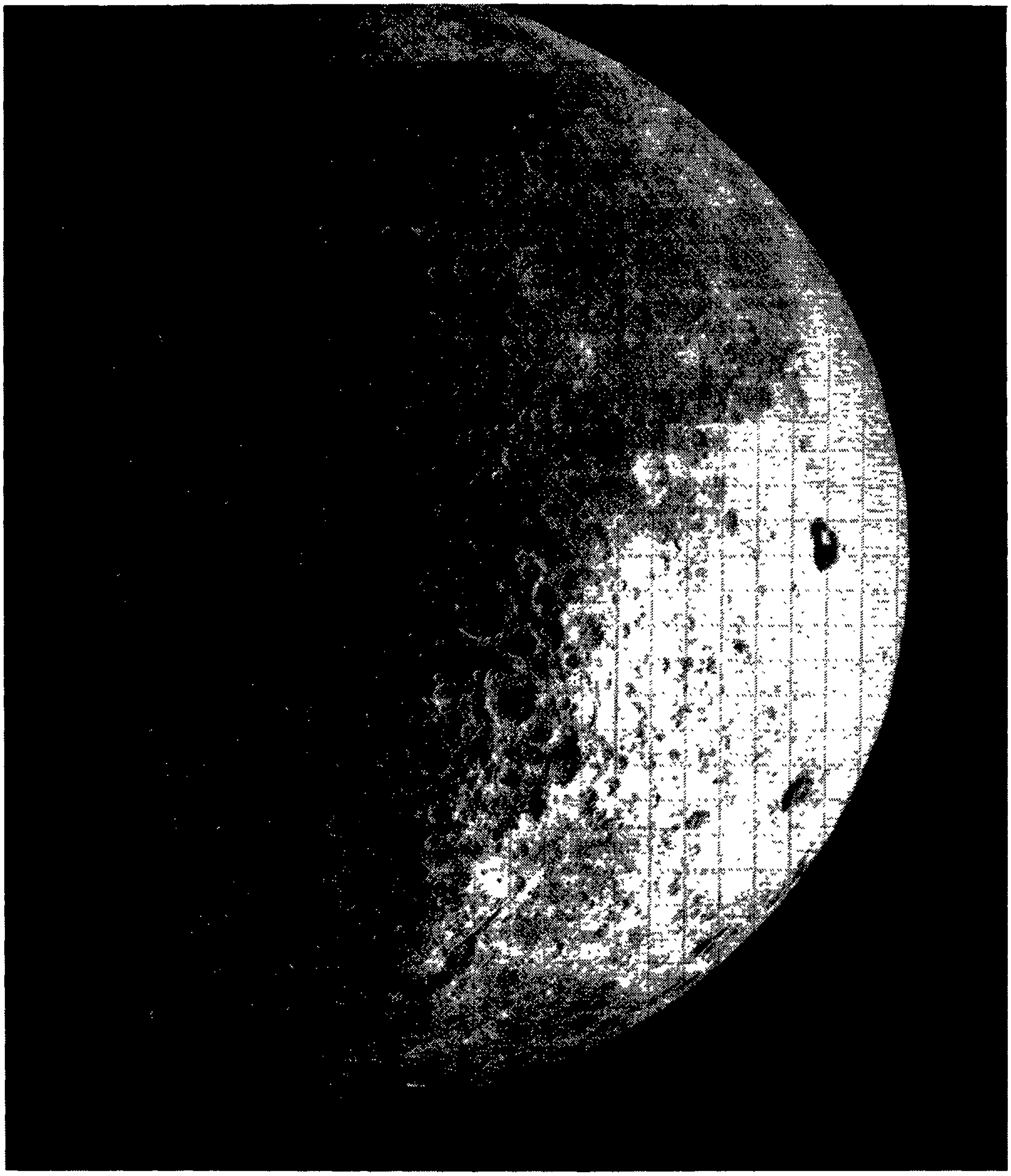

Fig. 11. Mare Australe (Lunar Orbiter IV-10M).

flooded with mare material considerably after the mare material had been deposited outside.

In the southern part of Mare Australe, large mare-filled craters display N-S, NW-SE and NE-SW trending wrinkle ridges (these are the prevailing directions of the so-called *lunar grid*, along which rilles, crater walls and other linear elements are aligned). In one or two rare instances, these wrinkle ridges continue into the adjacent highlands as a ridge or fault scarp. Some craters, particularly south of Lyot, have been deformed.

Flow structures are visible on the floors of Moulton and Chamberlin craters (on the northern tip of Rima Schrödinger).

7. Conclusions

A study of the Lunar Orbiter and Apollo photographs of Tsiolkovsky and Mare Orientale, as examples of lava-filled impact structures, has revealed that the mare lavas must stem from internal melting, because a considerable time interval has elapsed between the time of basin excavation and basaltic extrusions. This is effectively shown by the lower crater densities on the lava filling of Mare Orientale than on its ejecta blanket. The chemistry and the ages of the Apollo samples also support this consideration (see below).

Mare-type lavas are not only confined to large circular basins, but also fill irregular depressions, like Mare Australe, where evidence for different flooding episodes has been observed. In addition, probably shock-melted floors of certain craters (i.e., Tsiolkovsky) can be readily distinguished from mare-type lava flooding.

The Apollo 14 and 15 missions, furthermore, have furnished data which strongly suggest that the Moon experienced internal melting early in its history. Analyses of lunar rocks indicate that the moon's surface is not chemically homogeneous and has undergone igneous differentiation. The highlands are much richer in Al_2O_3 and lower in FeO and TiO_2 than the maria (Adler, 1972; LSPET, 1971; Wood, 1970). High pressure studies on lunar material have shown that the chemical composition of the Moon at depth cannot be identical to the mare basalts, because these would invert above 10 kbar (200 km depth) and 1100°C to a much denser rock such as eclogite (Ringwood, 1970, 1972). Sr^{87}/Sr^{86} isotope ratios suggest that the Moon underwent a primordial fractionation about 4.5–4.6 b.y. ago (Wetherill, 1971). Melting presumably produced a feldspar-rich crust. The evidence for chemical differentiation and early melting of the Moon's outer regions is further strengthened by the seismic results, which present the picture of a layered moon (Toksöz *et al.*, 1972).

The dating of Apollo 14 and 15 rocks has confirmed that the lava flooding of a circular mare basin has occurred long after its initial formation (Papanastassiou and Wasserburg, 1971; Alexander *et al.*, 1972). The age of 3.8–3.9 b.y. for the Fra Mauro Formation (the ejecta blanket of Mare Imbrium) and the 3.3 b.y. old basalt from Hadley Rille (the latest lava filling of Mare Imbrium) show that a half billion years elapsed between basin excavation and final filling.

Clearly, volcanic processes have played as important a role as meteoritic impacts, in shaping and modifying the lunar surface.

Acknowledgments

The writer expresses appreciation to Dr R. Jastrow for helpful advice and discussions. This research was carried out as the Goddard Institute for Space Studies under a National Academy of Sciences research associateship.

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